BELLCOMM, INC.
1100 Seventeenth Street, N.W. Washington, D.C. 20036

SUBJECT: Current Program and Considerations of the Future for Earth Resources Survey by Remote Sensing - Case 710

DATE: May 6, 1968

FROM: F. G. Allen
B. E. Sabels

## ABSTRACT

This memorandum is based on material gathered by the authors to assist Dr. Homer Newell in preparation for an address given at the Fifth Symposium on Remote Sensing of the Environment, University of Michigan, in April, 1968.

The field of orbital sensing of the earth's resources has not yet seen the launch of its first satellite, in contrast to the fields of meteorology and geodesy, in which operational satellite programs have been rapidly established in the past six years. Earth resources sensing has been retarded by technical complexity of data sensing and interpretation together with the need for coordination of several user organizations. Notable progress has been made, however, in ground and aircraft programs in identification of signatures of certain crops and minerals and in automatic processing of multi-spectral infrared imagery data. The usefulness of applications to oceanography, agriculture, forestry, and hydrology has now been sufficiently demonstrated that satellites could be launched and put to use in these areas in about two years.

The National Academy of Sciences Summer Study of 1967 has endorsed the future potential of remote sensing of resources enthusiastically.

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MEMORANDUM FOR FILE

## I. INTRODUCTION

It is now six years since the first symposium on Remote Sensing of the Environment was held in mid-February of 1962. That symposium offered much hope of things to come but displayed little data or hard evidence of accomplishments. Today it is helpful in gaining perspective to look back over the past six years to note our progress and find where we now stand.

Today, meteorological data from satellites are supplied to many countries on a routine basis and satellite communications links are commonplace. Photographs of the entire earth from synchronous orbit and communications from aircraft via satellite to earth have been demonstrated with the ATS-1 satellite. Ships navigate via the Navy's Transit satellites, and geodesy measurements are underway using Geos-A and Pageos-1 satellites. The Gemini color photographs of the earth have indicated the great range of uses for satellite photography.

Yet, it is striking that up to now we have not yet conducted any systematic sensing of the earth's natural resources.

A survey of the impressive volume of work during the past six years documented in the proceedings of the intervening symposia indicates that a long road existed between the early hopes for remote resource sensing expressed in 1962 and operational space systems. A great amount of data has been taken during the past six years in the laboratory and from aircraft over ground truth sites. The effort has been to determine just how great the potential for remote sensing of resources really is, and what techniques merit earliest trials.

The rest of this paper will summarize some of the progress made, assess current needs and problem areas, and then sketch some of the most promising methods for future use.

## II. ADVANCES IN SATELLITE SENSING PROGRAMS IN LAST SIX YEARS

### A. Meteorology

Progress in establishing an operational satellite program in meteorology has been rapid, and benefits are now accruing from our satellite systems.

Some of the highlights in our advances since Tiros IV have been: (Figure 1)

1. Automatic Picture Transmission System (APT) initiated in 1963 with Tiros VIII, allowing real-time readout of local cloud pictures from inexpensive portable ground stations;

2. High resolution infrared imagery allowing night time cloud cover determinations, first achieved in Nimbus I in 1964;

3. Tiros X placed in sun-synchronous orbit in July of 1965, spin-stabilized with two wide-angle TV cameras;

4. Tiros operational satellite system first established with ESSA I in February, 1966;

5. ESSA II in Tiros operational series in polar sun-synchronous orbit in February, 1966; readout of daylight cloud cover by Automatic Picture Transmission TV system.

6. Nimbus II in May, 1966, First Advanced Vidicon Camera System. Added a medium resolution IR radiometer in five spectral regions for earth heat balance, HRIR readout by APT and orbit data shown on APT. (Figures 2 and 3).

7. ESSA III in October, 1966 using first Advanced Vidicon Camera System in Tiros operational system.

8. ATS-1 in December, 1966 (Applications Technology Satellite) in earth-synchronous orbit. First spin-scan camera giving cloud cover over entire disk of the earth.

These accomplishments over the past few years (note particularly 1966!) are truly impressive, particularly when one considers the long lead time between inception and flight of a new system.

B. Geodesy

In geodesy, systematic research and development have made progress since NASA's Geodetic Satellite Program was established in 1962. Two years later, program operations were initiated with Beacon B (October, 1964) and C (April, 1965), which carried geodetic quality Doppler transmitters and corner reflectors for laser ranging. These were followed by GEOS-I in November, 1965 and Pageos-I in June, 1966, the first two satellites with capabilities and orbital parameters designed specifically for high-precision geodesy. (Figure 4)

GEOS-I was the first satellite to incorporate instrumentation for all of the five major current geodetic observation systems employed by the DOD, the U. S. Coast and Geodetic Survey, and NASA. It carries flashing xenon lights, corner reflectors for laser tracking, Doppler transmitters, a SECOR (Sequential Collation of Range) ranging transponder, and the NASA GSFC range and range-rate transponder. During its 12 months of full operational activity it was observed daily by 110 different ground stations and provided the first direct inter-comparison of results from all of the geodetic measuring systems. Pageos-I, a 100 foot Echo-I type balloon, occupies a high-altitude orbit permitting observation by stations as much as 3000 miles apart. It is currently observed by 43 stations, and has made it possible for the first time to establish a closed observation line around the world.

Data from the tracking of these satellites are being used to help establish a unified worldwide geocentric reference system accurate to $\pm$ 10 meters and define the earth's gravitational field including anomalies with wavelengths as short as 1500 miles.

Only preliminary results are available so far, and a considerable amount of work remains to be done to reconcile the different tracking systems and accurately determine the amount and type of error that exists in each. But the feasibility of these objectives has been demonstrated, and their accomplishment is now simply an operational question. In addition, the results of the program have already significantly increased our knowledge of the shape of the earth, its strength, and its internal mass distribution. Their impact is beginning to be felt in the fields of geology and geophysics.

### C. Other Fields

Compared to meteorology and geodesy where operational satellite programs have been in progress now for several years, other fields of earth resources sensing are in their infancy. No satellites have yet been launched, even in an R&D phase, addressed to remote sensing for oceanography, forestry, agriculture, hydrology, or geology. Why, we must ask ourselves, has remote sensing in these fields developed so slowly, and where do we stand today?

There are basically two reasons why meteorology and geodesy led the other disciplines.

First, the space experiments which had to be performed in meteorology and geodesy were simplier, in that fewer variables were involved demanding lower resolution and simplier interpretation, than for solid earth disciplines.

Second, organizations were ready to put space experiments into orbit. The Weather Bureau had launched balloons and rockets, as had the Navy Department and other students of the atmosphere. The opportunity of advancement by satellite operation was quickly recognized and used.

The only data we now possess from satellite altitudes relevant to resource sensing has come indirectly from color photography of the earth in the Gemini Program and from photography and infrared imagery of the earth from Nimbus II. Photography from the ATS-I satellite in synchronous orbit and recently from the Apollo 501 mission at 9000 miles, has provided useful oceanographic as well as meteorological information. We do now have, of course, a great deal of data in most fields from aircraft altitude.

The Gemini photographs, taken with a Hasselbladt 70 mm camera through the windows of the Gemini IV spacecraft - not an ideal photographic procedure - display the enormous potential of systematic satellite color photography of the earth's surface. With resolution down to about 200 feet these photographs prove that many goals in agriculture, forestry, oceanography, geology and cartography can be readily achieved by straightforward high quality photography in the visible. Some specific examples of geologic returns from the color photography in Gemini were the correction of geologic maps of Australia, South America, Africa, and Mexico from a total of 1400 pictures, including:

- disclosure of many geologic structures and rock units in Baja California that were not mapped before;
- a major volcanic field dating from the glacial age in Mexico that did not appear on the latest geologic map of 1965;
- corrections applied to the best topographic maps available of Saudi Arabia;
- regional distribution of sand dunes in the Namib Desert, which are a lead to diamonds occurring in alluvium between the dunes;
- location of a new potential ore deposit in New Mexico.

Also demonstrated by the Gemini photographs were potential benefits to commercial fishing through detailed indication of currents and sediments in shrimp-fishing areas near shore in the Gulf of Mexico. Other Gemini photographs of the Imperial Valley, California indicate levels of salination in some fields, and show contrast between well-drained and poorly-drained areas.

The infrared images taken with Nimbus II illustrate warm water currents, water budget of agricultural areas - well drained or poorly drained - crop status due to water supply, and extent of regional ice and snow cover.

We turn now to advances made in the past six years in earth resources sensing in ground-based laboratories and from aircraft.

## III. ADVANCES IN LAST SIX YEARS IN GROUND AND AIRCRAFT PROGRAM

### A. Oceanography

The large scale features of the oceans are dynamic and can only be monitored adequately with frequent repetitive measurements over wide areas. Because most areas of the oceans are never seen by man, oceanography lends itself ideally for remote sensing by satellites. The oceanographic features studied and developed to the point of satellite applicability are sea surface temperature and currents, sea state, sea ice, and marine life detection.

1. Sea Surface Temperature and Currents

Sea surface temperature gradients and discontinuities have been studied from aircraft in the visible, infrared and microwave regions of the spectrum. The visible and infrared regions are available for sensing only during cloud-free conditions, the infrared is useful at night as well as day, and microwave is useful under all conditions, including cloud cover. The infrared image shown in Figure 5, taken off Cape Hatteras from aircraft altitude, vividly portrays the contrast between the colder water (light) and the warmer Gulf stream water (dark).

The graph included in this figure is based on measurements made at approximately the same time with a calibrated airborne radiation thermometer. The sharp change of eight degrees centigrade corresponds roughly to the boundary area shown in the image. While these data were taken from aircraft, similar contrasts have been detected from Nimbus II high resolution IR imagery from an altitude of 1150 km. An example is Figure 6. It shows the Gulf stream off the U. S. East Coast over a distance of 1600 km. Using the computer gray scale conversion technique it is possible to plot grid maps which show greater detail in temperature contrast than can be obtained from the direct image. The area east of Cape Hatteras is shown in such a computer plot of Figure 7.

Optical systems for detecting ocean surface features are hampered by cloud cover. However, with a broad overview, it is possible to take advantage of cloud patterns to deduce ocean temperature contrasts and wind direction and speed, particularly in imagery from very high altitude, as provided by the ATS-I satellite at 22,000 miles altitude (Figures 8,9). Color photographs taken in the Apollo 501 mission near apogee of 9000 miles are of high quality and can provide even more useful results of this sort (Figure 10).

2. Sea State

Scientists have long been searching for a method to measure sea state in all kinds of weather on an ocean-wide basis as an aid to the shipping industry and for weather forecasting. It is common practice to infer sea state conditions from wind reports. One method of measuring sea state is the analysis of wave patterns and sun glitter in aircraft photographs of the sea surface. A recent advance in this area uses a laser technique to analyze the photograph (Figure 11), as performed by the U. S. Navy. The Fourier transform of the photograph on the left appears on the right in the Figure. In this transform, density distribution represents wave slope distribution, wave direction is proportional to azimuth, and radius from the center is proportional to wave frequency. This step may lead to rapid automatic processing of large amounts of photographic data. The same technique, incidentally, is applicable to solid surfaces, where geological structure can be brought out by Fourier transforms of photographs.

Passive microwave and radar reflectance measurements are currently the most promising for sea state determination since they are sensitive to wave characteristics and can be made without appreciable attenuation in the presence of storms and clouds. Investigators have shown recently that by plotting reflected radar energy against the angle of incidence at the sea surface, one obtains well separated signatures for various states of sea roughness. Examples are shown in Figure 12. The data were substantiated by MSC aircraft measurements in late 1967 off New-foundland.

Because 19.4 Ghz passive microwave sensors are insensitive to sea temperatures, the sea state can be studied at that frequency without interference from sea temperature variation. Figure 13 shows ocean brightness temperatures versus sea state and incidence angle. It is seen that at about 50° incidence, there is a maximum separation of brightness values corresponding to different sea surface roughness. This measurement was done with the instrument designed for a Nimbus measurement of cloud top temperatures and demonstrates one of the few instances where an experiment is useful for an application other than that for which it was intended.

### 3. Sea Ice

Adequate knowledge of the distribution of ice in the Arctic and Antarctic is lacking. All-weather information on ice and icebergs has applications for meteorological services, ice patrols, and the shipping industry. Television and IR sea ice data obtained with the polar-orbiting meteorological satellites TIROS, ESSA, and NIMBUS have been used to support shipping activities. However, things have not always been that easy.

Ever since the Titanic disaster in 1912, the U. S. Coast Guard has carried out ice patrol surveys. These patrols were initially conducted by eye from shipboard and later from aircraft, which often meant flying at 50 feet above sea level below the clouds. Several planes were lost in collisions with icebergs. After World War II, radar was used, again first from low altitude and as a safeguard for the ice survey plane. Since 1962, the Coast Guard flies huge microwave scanning systems installed in C-130 planes (Figure 14), and it is hoped that this demanding and expensive operation can be taken over by satellites. A C-130 costs on the order of $2,000 per hour to operate, and during the ice season one of two planes is on the job constantly. A 10 million dollar weather satellite lasting for five years would cost only $200 per hour, and would give varied services on a global basis. A microwave water/ice interface trace taken from aircraft is given in Figure 15.

### 4. Marine Biology

Photographs from aircraft of schools of fish are well known (Figure 16). Small spotter planes have been used by commercial fishing fleets for several years. Aside from surface temperature measurements, which provide important evidence for preferred fish locations, other applications are in the R&D stage, such as IR and narrow-band visible region spectrometry and photography.

### 5. Summary of Oceanography

All in all, the field of oceanography shows considerable progress in the application of remote sensing techniques, in addition to techniques proven in orbit. It may already be justifiable to propose an "Oceanographic Nimbus Program", with the goals of monitoring sea state, ice location and surface temperature. Such a program could become operational in about two years.

## B. Forestry, Agriculture, and Geography

In turning from oceanography to forestry and agriculture, we are reducing the size of the objects of remote study from hundreds of miles to miles or hundreds of feet. The identification of individual forest species or crops requires much higher resolution than oceanographic sensing. The fact that there are seasonal and even diurnal changes in spectral signatures introduces new complications.

Operational techniques in agriculture, forestry and geography include photography in the visible and IR region of the spectrum. Aerial photographs and maps are the proven basis for land use, soil surveys, forest inventories, and engineering plans. As indicated at the outset, Gemini photographs have contributed already to the improvement of these records, and we hope to get more than 700 new photographs from the forthcoming AS 502 unmanned Apollo test flight between $\pm 30°$ latitude.

There is now considerable evidence that infrared photography permits early detection of diseased crops or trees. A recent example of this has been the use of Ektachrome IR photography for early determination of brown soft-scale and black-fly infestation on citrus trees in Weslaco, Texas.

Another operational remote sensing application operated in the western mountain states is infrared forest fire monitoring from aircraft, performed by the Department of Agriculture. This system can be readily converted to a satellite application, including a volcano watch.

Perhaps, the most significant innovation in remote sensing in agriculture is the use of IR and visible region imagery in several wavelengths from aircraft to determine crop species and variety, relative size and maturity of crops, and relative amounts of vegetation observed. In addition, microwave imagery has been demonstrated to identify soil types, and moisture content in a manner possibly superior to IR sensing. Of particular significance is the fact that a large number of spectral bands - up to 18 - are being used, and that the multiplicity of sensors provides a much greater degree of reliability than the use of single bands. This approach is identical with the mathematical problem of solving a system of equations with a number of unknowns. Examples of the problem and the solution are shown in Figure 17. Oats, soybeans, corn, wheat and alfalfa give fairly similar spectral responses in any one of several wave bands between 0.32 and 14 microns. But a computerized evaluation of the spectra demonstrates that the multiple system of equations does have a unique solution, and that the crops can be identified and printed out in a map which can be compared with a photograph (Figure 18). Success rates of 80-90% in the identification of some crops such as wheat have been achieved in test flights last year, and it is expected that further progress will be made with the incorporation of new equipment in the NASA aircraft in Houston. Operation of a multispectral imager from high altitude aircraft is now planned in a program to test this technique for satellite application.

The same principle has been applied in the passive and active microwave region using multifrequency, dual polarization for soil analysis. Computer maps of soil and rock types have been prepared. It remains to be seen whether it is feasible to produce such maps from space or whether one should restrict the capability to aircraft altitudes. This will depend on the evolution of our resolution and data handling capability. But the progress is encouraging.

C. Hydrology and Geology

Operational programs in hydrology and geology remote sensing are still all from aircraft. Aside from the demonstrated potential of color photography it appears that it will take some time to sort out and develop other promising remote sensing techniques in these fields. During the past six years, it has been recognized that a definite effort is necessary to relate the complex spectra observed at aircraft altitude to the multitude of variables on the ground. A "ground truth" program has been created, with the objective of measuring absolutely the parameters of grain size, ground temperature, soil moisture, rock composition, air temperature and wind speed, etc., and then assessing the degree to which these parameters are reflected in the signal recorded from the aircraft. One can identify over 100 individual ground truth parameters. This effort has been most thoroughly implemented to date in agriculture, but is also being advanced by other user agencies. There is not doubt that it is most necessary in geology and hydrology where the signficant parameters are harder to identify.

At this point in time, NASA has a network of some 150 aircraft test sites spread all over the U. S. (Figure 19). Most of these are geological and hydrological; some are geographic, agricultural and oceanographic. We have now two aircraft with operating remote sensors, as shown in Figure 20, and we are planning to add both low and high flying aircraft to the program. For the first time, we have a data handling capability which allows us to process recorded data, and to incorporate ground truth and meteorological information. While the program has been operating for several years on a minimum budget, not allowing acquisition of optimized equipment, we are now in a position to procure specially developed sensors for our aircraft sensor payloads. This new impetus in the program will particularly intensify the progress in hydrology and geology.

Aircraft sensing in hydrology has been used to trace fresh water discharge in salt water and pollution discharge into fresh water, largely on the basis of temperature differences identifiable by IR imagery. Similarly, IR imagery has been used to identify hot springs. Penetrating microwave sensing and remote sensing of fumarole (hot spring) activity by absorption techniques may help in detection of geothermal power sources, but have not yet been demonstrated.

Snow and water surveys are being carried out from aircraft, and all-weather microwave sensing even of subsurface water (soil moisture) is being carried out (Figure 21), using multiple frequency polarized systems. The spectacular cross-country survey flown with the Nimbus microwave scanner at 30,000 feet revealed Sierra Nevada snow packs and subterranean rivers in the St. Louis area through heavy cloud cover. Also, the Tennessee Valley Authority uses microwave sensors for watershed inventories.

In general, multiple-parameter, multichannel polarized sensing is being developed for geological application. This holds particularly for radar, microwave, and to some extent for IR. The results of this approach, coupled with effective ground truth programs, are yet to come.

Side-looking radar operated from aircraft has recently met with impressive interest on the part of various users. A major manufacturer intends to provide a service in imaging terrain on a cost per mile basis. Similar efforts are being made in microwave technology. The objective of these surveys is to bring out topographic, tectonic, hydrologic and geomorphic features more clearly than is possible by photography.

### Summary of Solid Earth Sensing Programs

It appears that a research and development satellite for remote sensing in agriculture, geology and related disciplines should be planned at this time. Useful applications of existing techniques have been sufficiently demonstrated now that a definition of a payload is a logical step.

## IV. NEEDS AND FUTURE PLANS

Up to this point we have discussed tangible results and on-going programs. We now turn briefly to identify areas of need and to discuss promising techniques that must still be proven.

A. Meteorology

In meteorology, despite our operational satellite system, we still lack much of the data essential for world-wide long-range weather forecasting. Currently, we get good global cloud-cover pictures, cloud motion and some ocean surface temperatures. We do not get three dimensional fields of density, wind velocity, temperature and water vapor content within the atmosphere itself. Yet, these are required before realistic weather models can be constructed and tested.

Promising techniques to meet these needs are:

1. Measurement of atmospheric temperature profiles by radiance inversion techniques. These involve measurements of radiation from the atmosphere looking vertically down from the spacecraft at several nearby wavelengths, in the IR or microwave regions. From the integrated absorption over the altitude and its variation with wavelength, the temperature profile can be reconstructed.

2. Atmospheric radio occultation between a satellite and a set of "slave" satellites to measure atmospheric density. The transmission path to each slave satellite samples a successively higher altitude above the earth, and as the whole system orbits, a continuous trace of the vertical density profile is taken along the path. (Figure 22).

3. Another potentially useful technique that needs testing is that of auto-correlation of radar, microwave, or optical signals in two crossed beams. By this method properties of the atmosphere at the particular height of beam-crossing may be extracted by analysis of the signals from both beams and reading out only that part of the signals showing cross-correlation. This method may be useful for measuring temperature, wind movement, clouds, rainfall and drop size. The double beam technique would require either well-separated antennas on booms on a single satellite, or two co-orbiting satellites. (Figure 23).

Until methods such as these can be made operational, high pressure weather balloons at various altitudes may have to be used and interrogated by satellites to supply the data needed for weather prediction to provide the state parameters in the atmosphere essential for long-range weather prediction.

As for eventual benefits, we can consult the 1967 Summer Study report of the National Academy of Sciences. The Study expects large annual economic benefits from the availability of a 5-10 day reliable weather forecast for a variety of weather-sensitive activities, such as the construction industry and agriculture. The Academy believes that annual benefits will exceed annual costs by a very large factor.

B. Geodesy

In geodesy, completion of the current programs will enable us to find the relative positions of any two points on earth with an accuracy somewhat better than that of conventional first-order triangulation. But geodetic science will not come to an end because of this. Far from it: just because space technology has so greatly increased the resources of geodesy, the imaginations of geodesists have leaped ahead to correspondingly ambitious new goals.

Key elements in new geodetic technology will be highly precise laser ranging devices, optical systems of very high resolution, atomic clocks, and a variety of sophisticated special instruments such as gravity gradiometers. Geodesists hope to use their new techniques to make direct measurements of the rates of continental drift and uplift, monitor the geometry of the ocean surfaces, keep track of the total water content of the polar ice caps and the world's glaciers, probe the interior of the earth by exploring its gravity anomalies, and measure the tidal and other mass motions of the atmosphere.

C. Oceanography

There are three areas of oceanography where we may look to major contributions from space in the future:

1. Sea surface state on all shipping lanes
2. Marine biological resources
3. The science of oceanography.

As for the first, we have mentioned that monitoring of ocean wave conditions and sea-ice has now been demonstrated by radar and microwave techniques from aircraft. It should be possible to extend this technique to satellites with few technical difficulties. Considering the large economic benefits predicted for the shipping industry, this program seems to merit early support.

As for marine biological resources, we have not yet demonstrated any techniques of direct usefulness, except surface temperature determination and color photography. To produce data of significance to the fishing industry we will need something like weekly global maps of surface temperature and chlorophyll concentration. Correlations between location of fish populations, chlorophyll concentration and surface temperature have been demonstrated in several instances.

Recent work measuring the optical properties of sea water with varying levels of chlorophyll offer hope of measuring chlorophyll concentration by remote sensing. Marked changes in color occur in the green, and a strong absorption line appears near 6800 Å (Figure 24). Color photography or spectroscopic determination of reflected light near this wavelength from a satellite may thus be effective for measuring surface chlorophyll levels.

Further possible information on marine life resources may come from oil slicks appearing near schools of fish. These might either be detected by detailed color photography, or, possibly by absorption spectroscopy highly sensitive to fish oil vapors above the slicks.

Research is needed to find what overall contributions to the science of oceanography can be made through surface observations. Classically, oceanographers have been interested in many properties far below the surface and many of these will probably never be accessible from space. However, satellite interrogation of ocean buoys, designed to supply depth measurements of temperature, salinity, and current will surely become useful.

If adequate satellite altimeters can be developed, oceanographers can gradually determine the true shape of the geoid, and ocean height deviations from this level will be extremely useful in determining the dynamics of ocean movement on both local and global scales.

In the long run, benefits from satellite oceanographic techniques can be expected to result in many large sectors of the economy, such as fisheries, industrial applications as coastal engineering, and ocean transportation. A few examples cited by the Academy of Sciences Study of 1967 include world freight shipping and world fishing industries. The Academy finds it safe to assume that any small-percentage savings accruing to industries would quickly give benefits many times greater than the cost of a satellite program.

## D. Agriculture, Forestry and Geology

The great need for technical advance in the areas of agriculture, forestry and geology, is the improved identification of the signature of various species. We have described recent advances showing that several techniques are now practical enough to be used with automated signature identification from aircraft. Higher reliability of identification and higher resolution is needed before we can make workable satellite systems.

One significant outcome of several years of agricultural ground and aircraft test programs has been the recent identification of a set of spectral bands in the infrared and visible that appears optimum for remote crop identification.

Some substantial laboratory investigations have recently shown that there are significant differences in the spectral reflectance from 0.4 to 2.0 microns of various types of silicate rock powders. The emission spectra of various rock types between 8 and 14 microns has been shown to vary sufficiently with composition, to permit significant identification when making spectral measurements on the ground from a distance of a few thousand feet.

Some problems of atmospheric absorption, resolution and noise must still be faced in going from aircraft to satellites. The high altitude aircraft test program is a step toward checking the absorption of the entire atmosphere. Increased geometric resolution should be achievable by increasing antenna size or power, camera focal lengths and detector sensitivities.

## V. SUMMARY AND CONCLUSIONS

We have talked about technical progress and remaining problems. We have not mentioned the very great problems of providing a data network and of organizing different users and even different countries in an overall workable system. Yet, these must be faced before we can begin to realize the potential of remote sensing. It is our hope that if we push on vigorously and demonstrate workable technologies, others will find ways to solve political and organization problems.

It is reassuring to find that the National Academy of Sciences report on last summer's study on Space Applications, has endorsed the future potential of remote sensing of resources so enthusiastically. I should like to close by quoting them:

> "Useful applications of space are unquestionably real, substantial, and potentially close at hand. A turning point has been reached, at which we can now describe with conviction and in some detail the many specific ways in which space vehicles and

space technology will become important elements in our economic, industrial, and social world. Applications that were speculative and vague only a few years ago now appear credible and attractive to the potential users. The space program has broken the plausibility barrier."

And later they state

"Our first general conclusion is that the potential economic benefits to our society from space systems are enormous. They may amount to billions of dollars per year to many diverse elements of our industry and commerce and thus to the public."

ACKNOWLEDGEMENTS

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Attachments
  Figure References
  Figures 1-24

NON-NASA SOURCES OF FIGURES

| | |
|---|---|
| #5 through 16 : | United States activities in Spacecraft Oceanography National Council on Marine Resources and Eng. Development, Oct. 1, 1967 |
| #14 | Sperry Microwave brochure |
| #17 and 18 | Purdue University Research Bulletin No. 832, July 1967 |
| #21 | Space General material |
| #24 | TRW Contract NASw-1658, Jan. 26, 1968 |

FIGURES

FIGURES (CONTINUED)

FIGURE 1

Meteorology Satellites

| | | |
|---|---|---|
| Tiros VIII | 21 Dec. 1963 | APT, real-time readout of cloud pictures |
| Nimbus I | 28 Aug. 1964 | HRIR night time cloud cover |
| Tiros X | 2 July 1965 | Two wide-angle (104°), TV cameras, spin-stabilized |
| ESSA I | 3 Feb. 1966 | Tiros operational satellite system (TV sensor system) |
| ESSA II | 28 Feb. 1966 | Local readout of daylight cloud cover by APT. Advanced cartwheel. |
| Nimbus II | 15 May 1966 | First advanced vidicon camera system - medium resolution IR radiometer in 5 spec. regions - HRIR readout by APT |
| ESSA III | 2 Oct. 1966 | First advanced vidicon camera in Tiros operational system |
| ATS I | 6 Dec. 1966 | Earth-synchronous orbit. First spin-scar camera firing cloud cover over entire disk. |

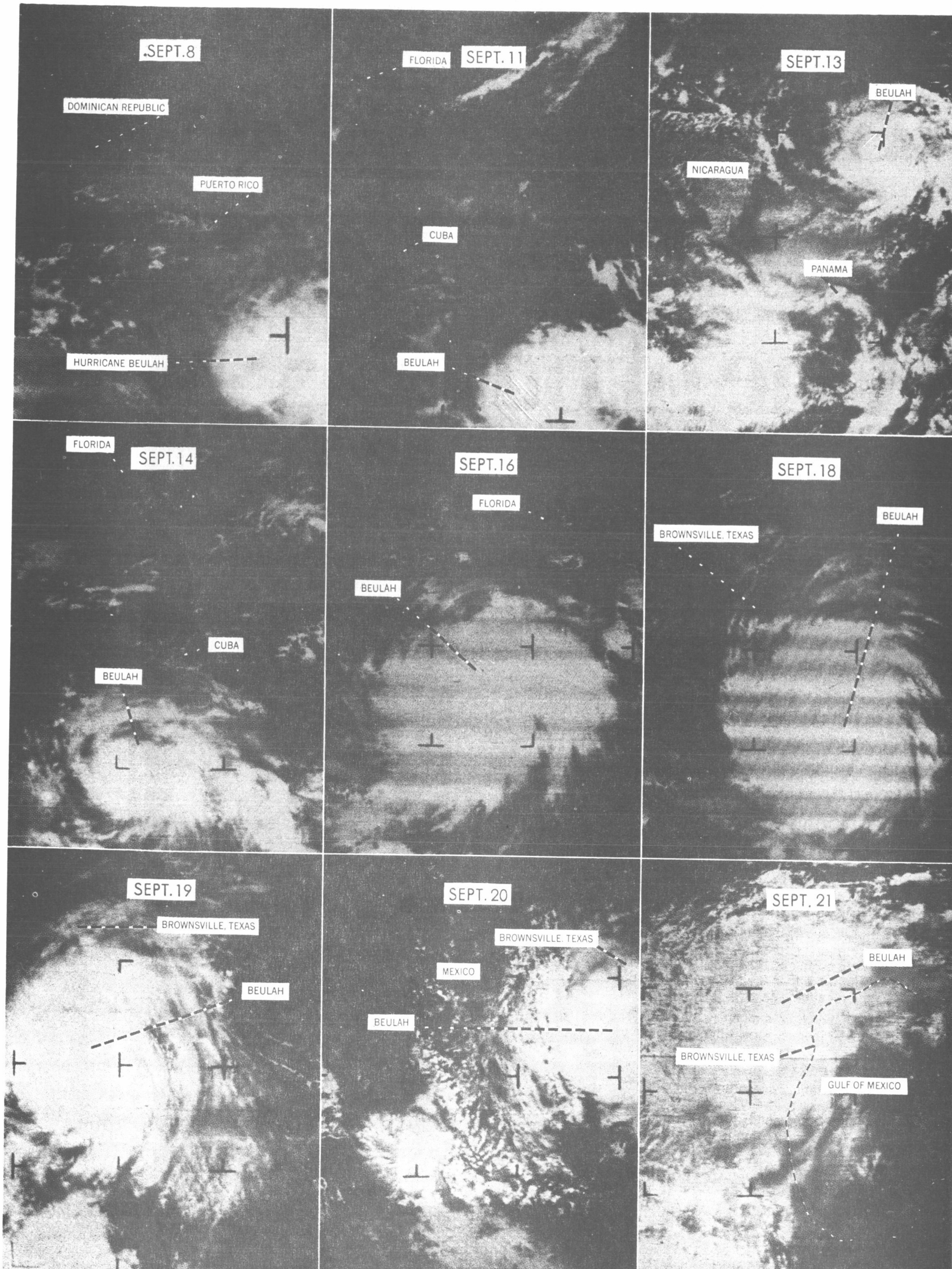



FIGURE 2 - CLOUD IMAGES NIMBUS II

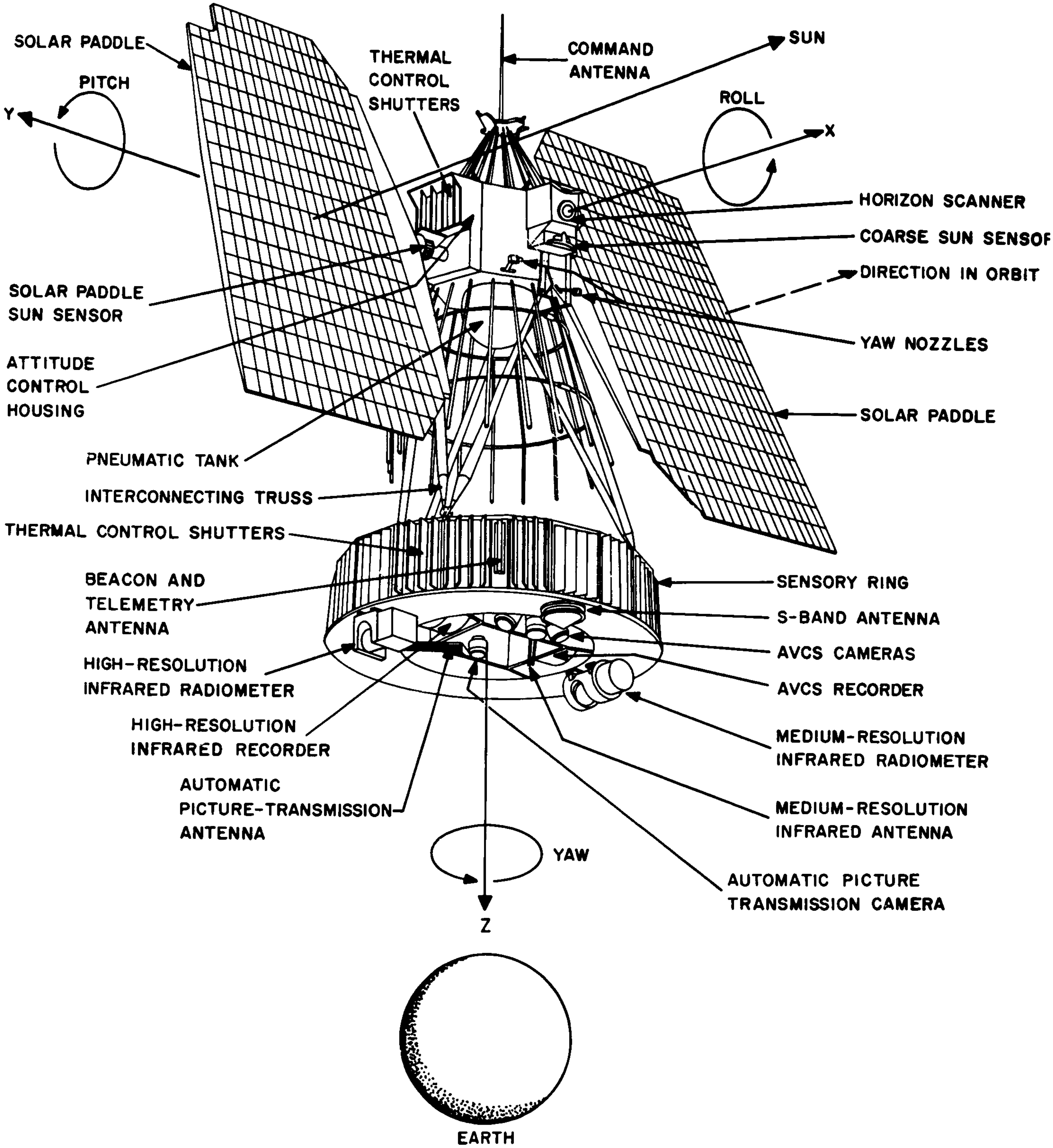



FIGURE 3 - NIMBUS II SPACECRAFT

| | | | |
|---|---|---|---|
| BEACON B | OCT. | 1964 | GEODETIC QUALITY DOPPLER TRANSMITTERS, |
| BEACON C | APRIL | 1965 | CORNER REFLECTORS FOR LASER RANGING |
| GEOS I | NOV. | 1965 | HIGH PRECISION GEODESY<br>FLASHING XENON LIGHTS, LASER TRACKING,<br>DOPPLER TRANSMITTERS, SECOR<br>RANGE-RATE TRANSPONDER<br>110 GROUND STATIONS FOR DAILY OBS. |
| PAGEOS I | JUNE | 1966 | HIGH PRECISION GEODESY<br>100 FOOT ECHO I - TYPE BALLON, HI-ALT.<br>OBSERVED BY 43 STATIONS AT THIS TIME |

FIGURE 4 - GEODESY SATELLITES

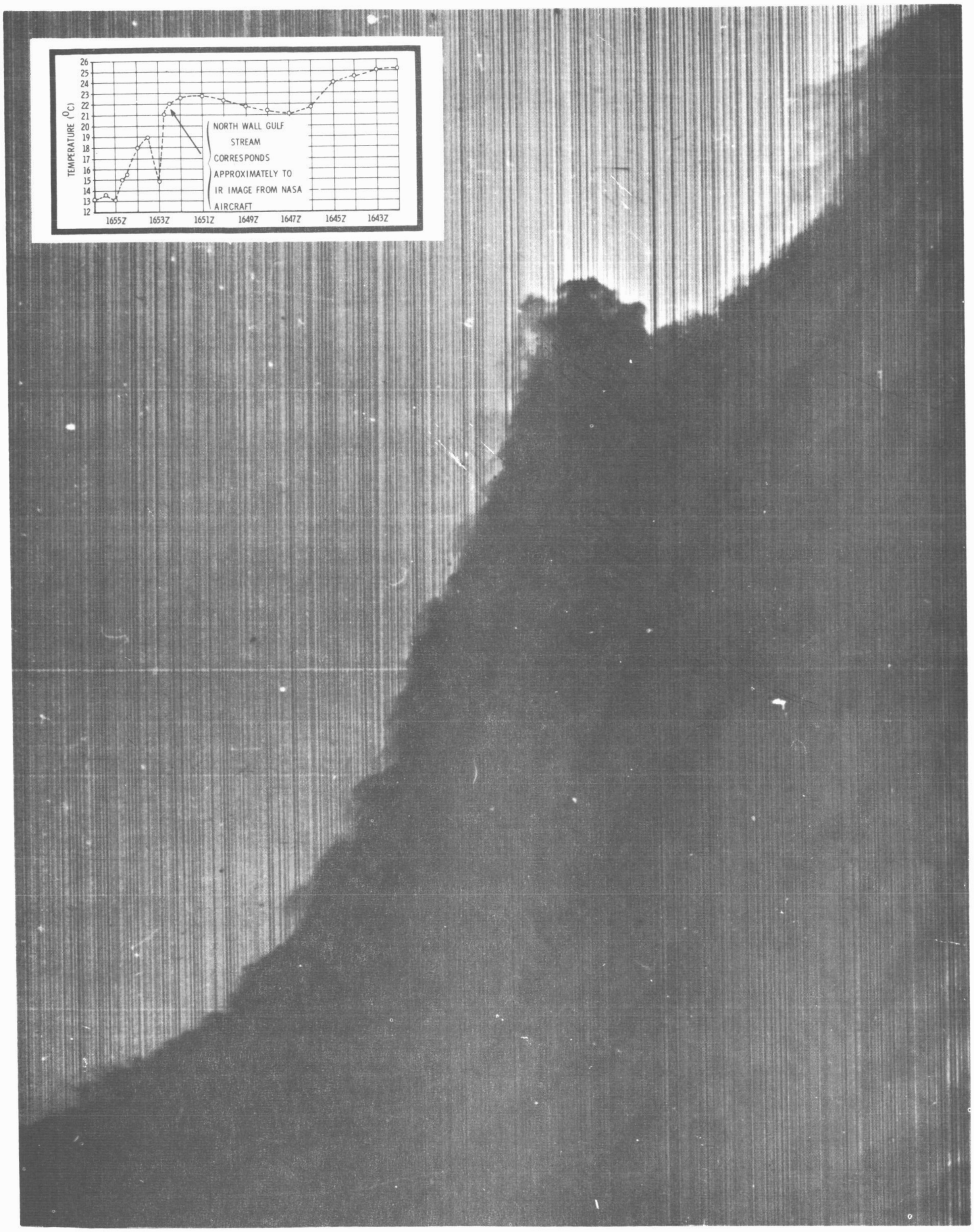



FIGURE 5 - AIRCRAFT IR IMAGE AND INSERT OF AIRBORNE RADIATION THERMOMETER GRAPH OF GULF STREAM OFF CAPE HATTERIAS, N.C., MARCH 12, 1966, NASA, U.S. NAVY


FIGURE 6 - NIMBUS II HRIR IMAGE OF THE GULF STREAM FOR OCTOBER 8, 1966, NASA. IMAGES OBTAINED AT NIGHT, AND THE LAND, BEING COLDER THAN THE WATER, STANDS OUT AS A LIGHTER GRAY

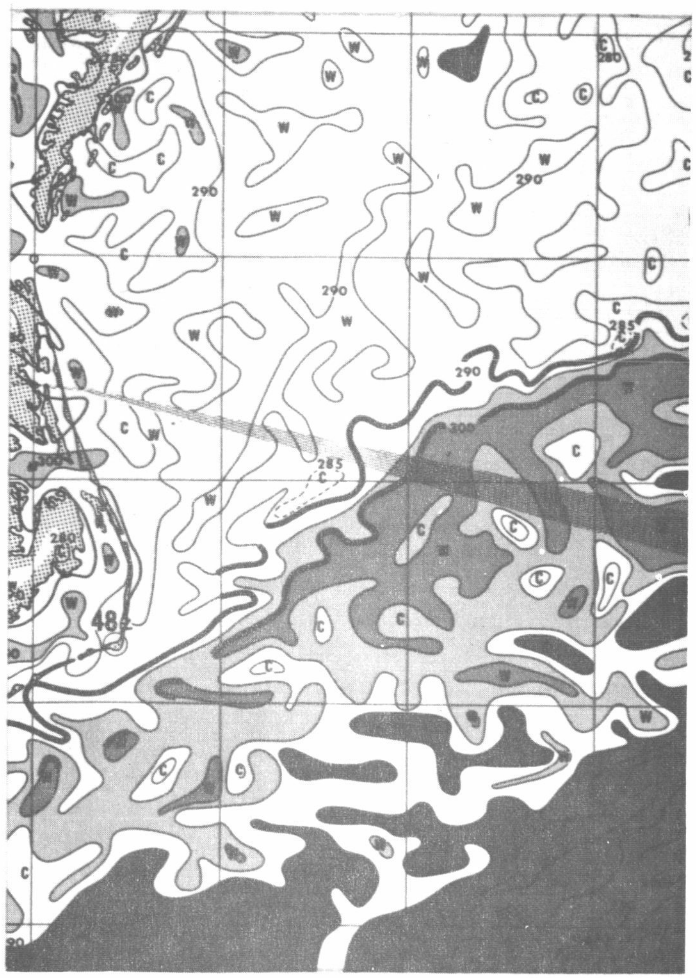


FIGURE 7 - TEMPERATURE ANALYSIS OF AREA EAST OF CAPE HATTERAS, N.C. DERIVED FROM NIMBUS II. HIGH RESOLUTION IR DIGITAL DATA, JUNE 2, 1966 (ALLISON AND WARNECKE, NASA)

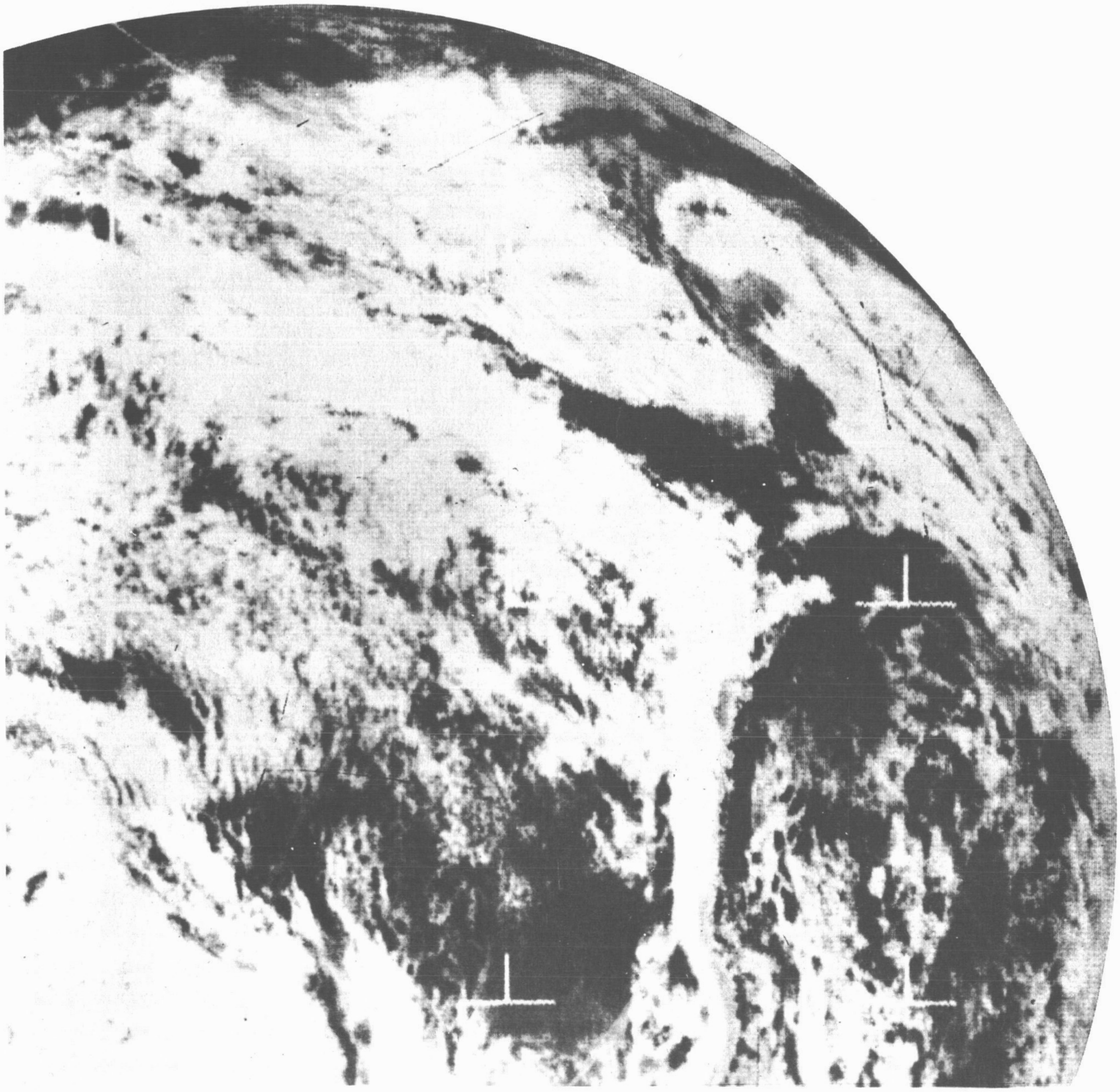


FIGURE 8 - ATS-I PHOTOGRAPH OF CLOUD PATTERNS OF THE EASTERN PACIFIC, APRIL 10, 1967, NASA

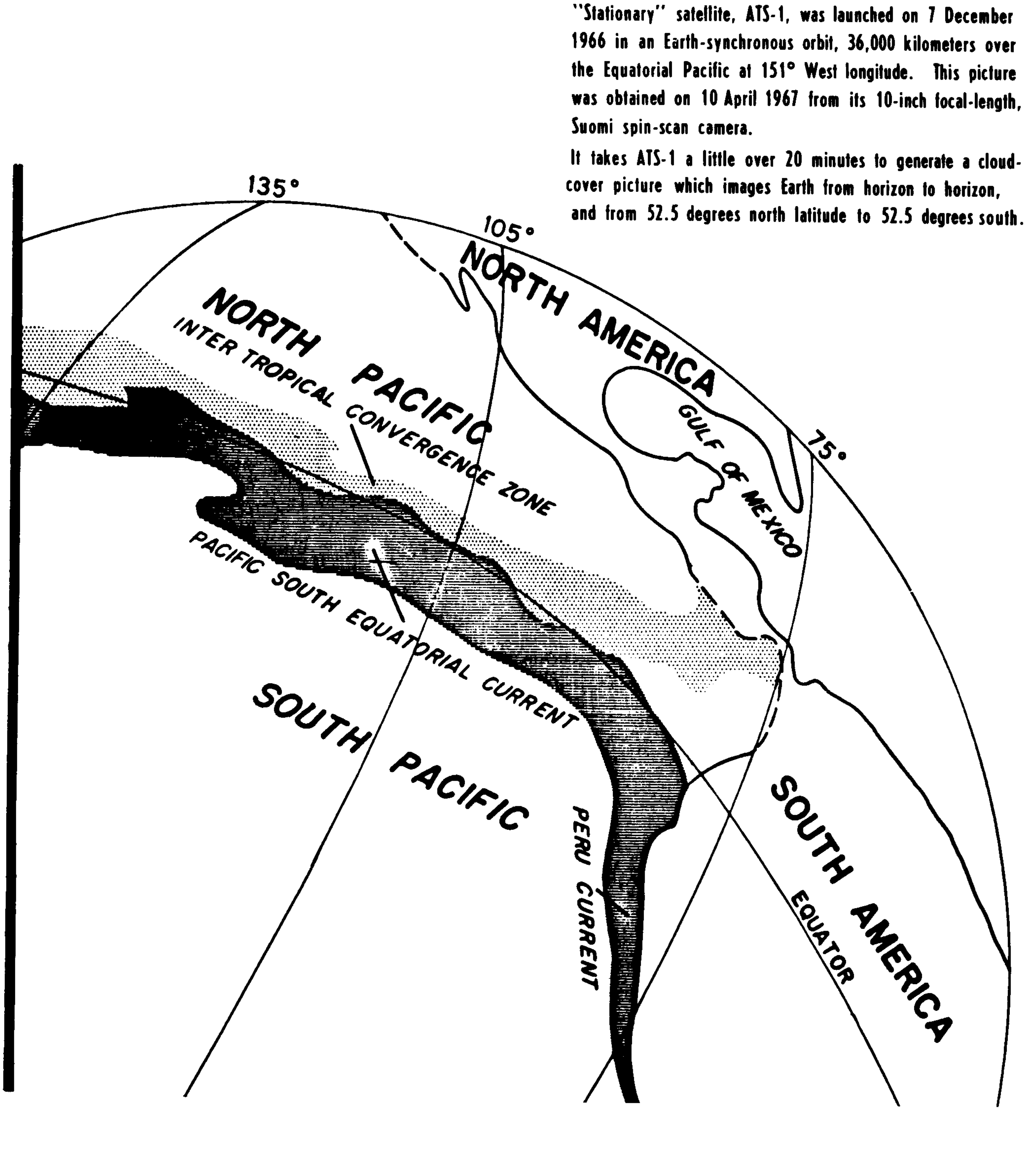



FIGURE 9 - RELATIONSHIP OF CLOUD PATTERNS TO MAJOR CURRENT SYSTEMS, JULY 1967, LaVIOLETTE, U.S. NAVY

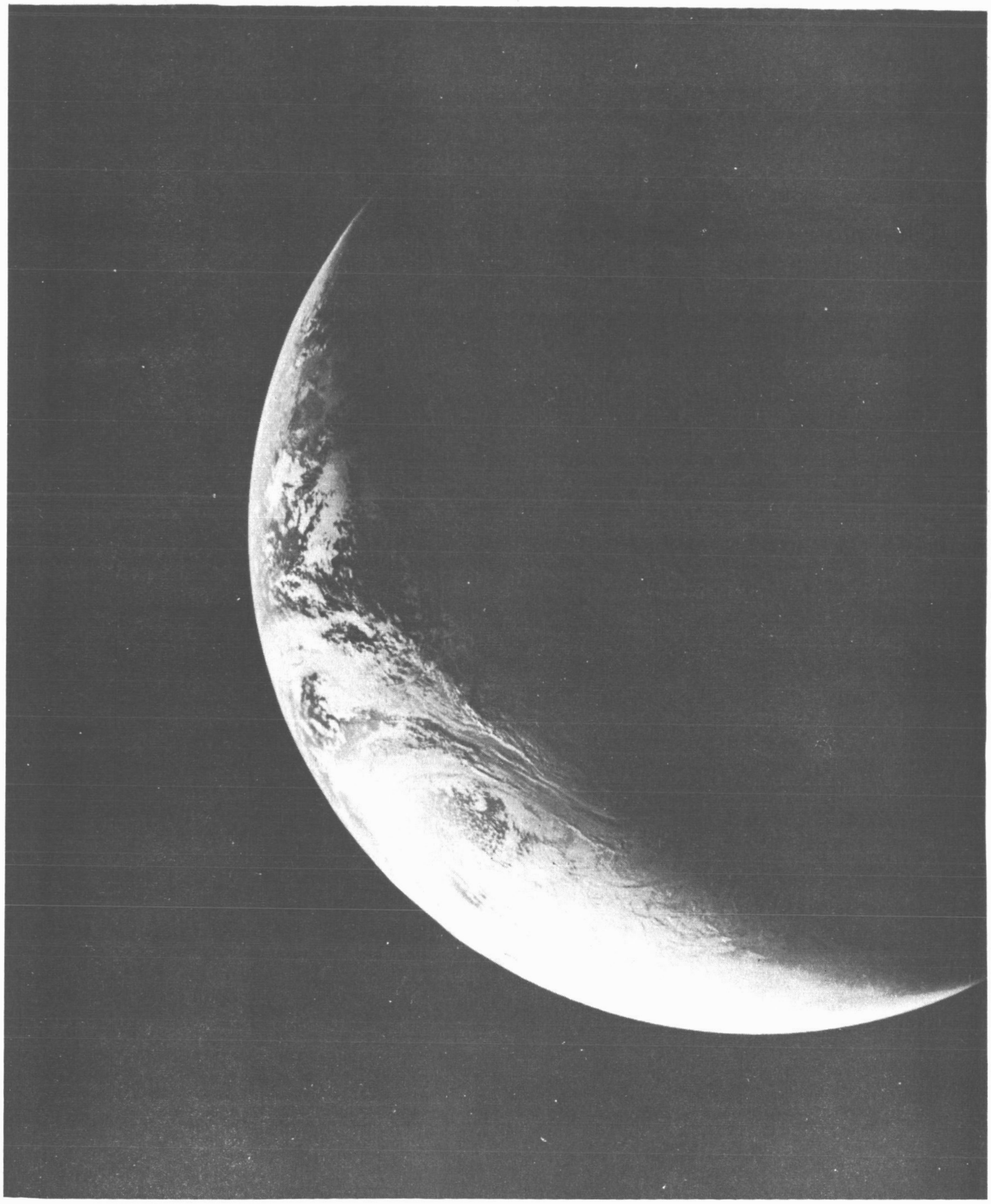


FIGURE 10 - APOLLO 501 PHOTOGRAPH FROM 9000 NM DISTANCE, 9 NOV. 1967

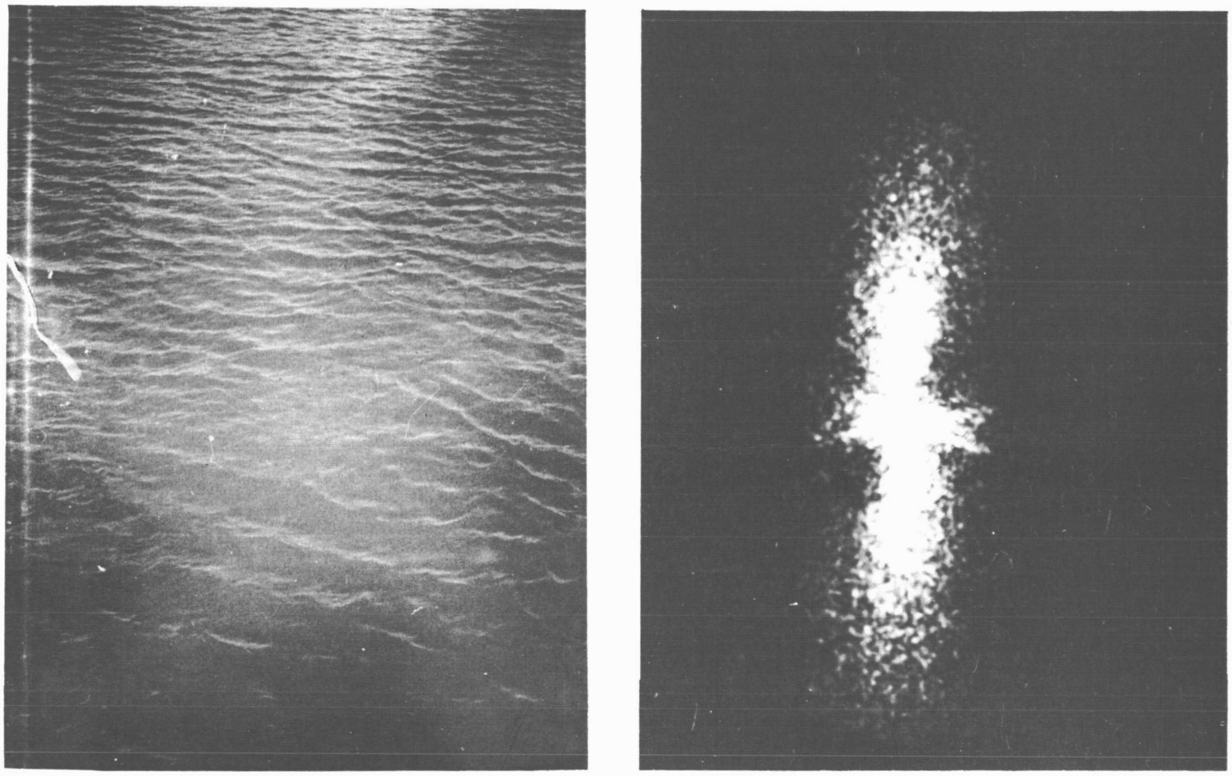


FIGURE 11 - PHOTOGRAPHIC ANALYSIS OF GLITTER, APRIL 1967, STILLWELL, U.S. NAVY - NEAR SURFACE PHOTOGRAPH AND FOURIER TRANSFORM OF GLITTER FOR SLOPE AND DIRECTION

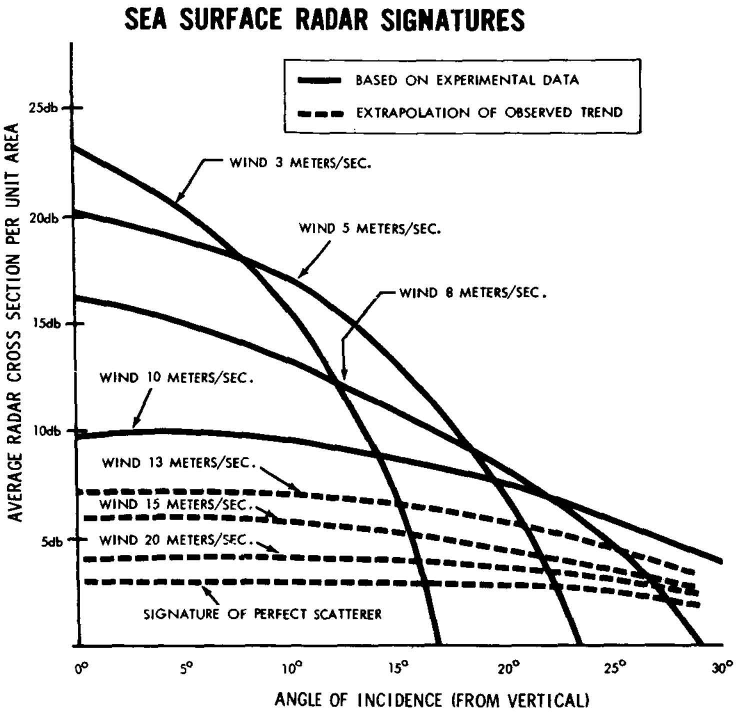



**FIGURE 12 - RADAR REFLECTIVITY FOR SEA CONDITIONS AT VARIOUS WIND SPEEDS AS A FUNCTION OF INCIDENCE ANGLE, JUNE 1967, PIERSON, NEW YORK UNIVERSITY**

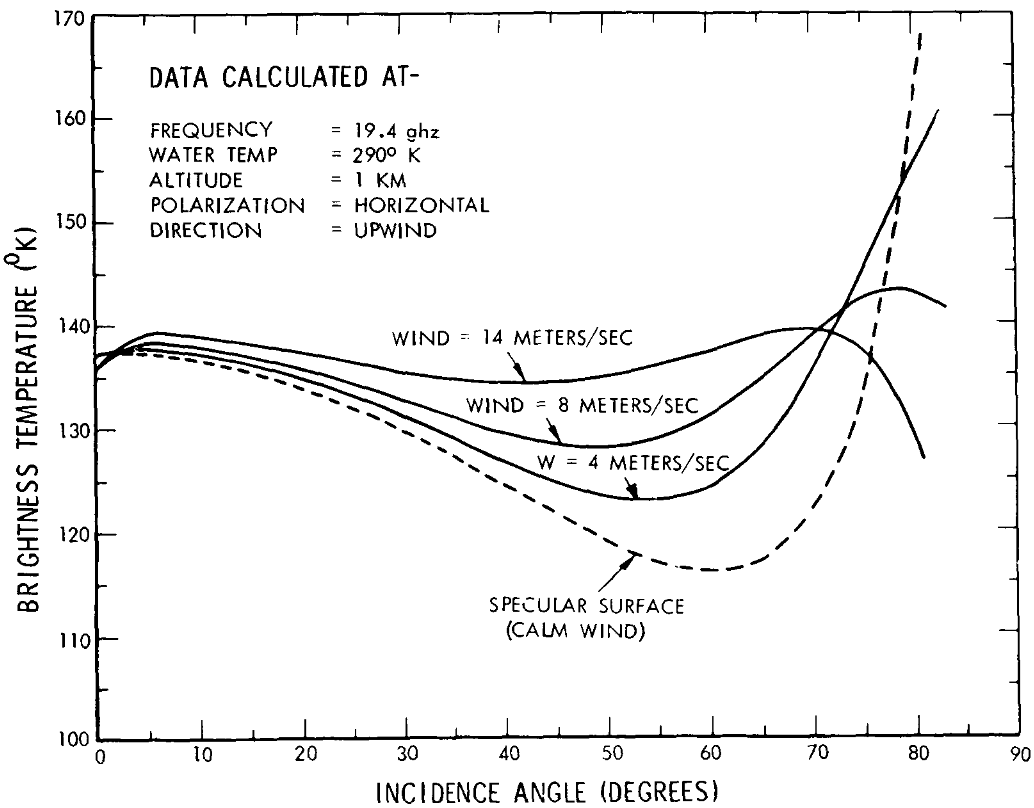



**FIGURE 13 - MICROWAVE BRIGHTNESS TEMPERATURE OF THE SEA SURFACE FOR VARIOUS WIND SPEEDS AS A FUNCTION OF INCIDENCE ANGLE; JANUARY 1967, STOGRYN, SPACE GENERAL CORP**


FIGURE 14 - GREAT WHITE HUNTER U.S.C.G. ICEBERG SURVEY

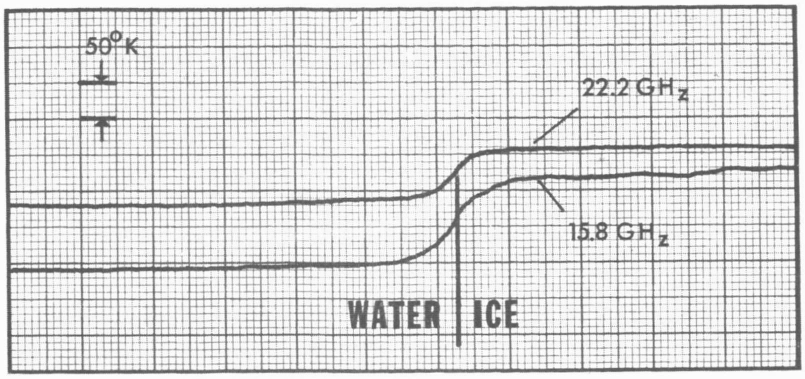



FIGURE 15 - PASSIVE MICROWAVE RADIOMETER TRACES OF ICE/WATER BOUNDARY - OFF LABRADOR COAST, APRIL 20, 1966, NASA, CRREL, U.S. ARMY

FIGURE 16 - AIRCRAFT PHOTO OF FISH SCHOOL OFF THE WEST COAST OF FLORIDA TAKEN WITH EKTACHROME FILM FROM 2500 FEET ALTITUDE; JAN. 1967, BULLIS, BUREAU OF COMMERCIAL FISHERIES

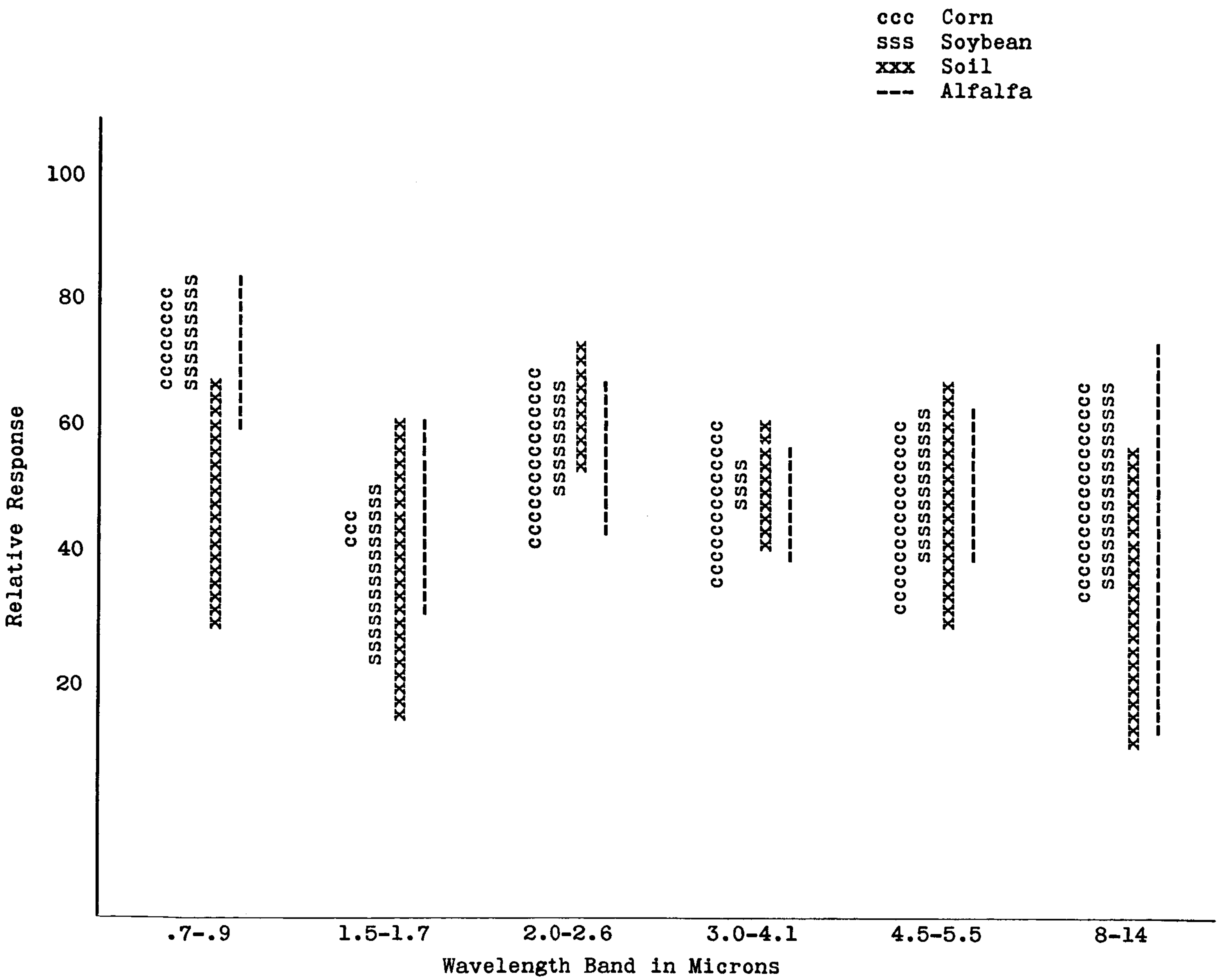



FIGURE 17 - THE DISTRIBUTION OF THE RELATIVE RESPONSE OF THREE DIFFERENT CROP COVERS AND BARE SOIL WITHIN 6 WAVELENGTH BANDS OBTAINED ON AUGUST 27, 1964. PURDUE EXPERIMENTAL FARM

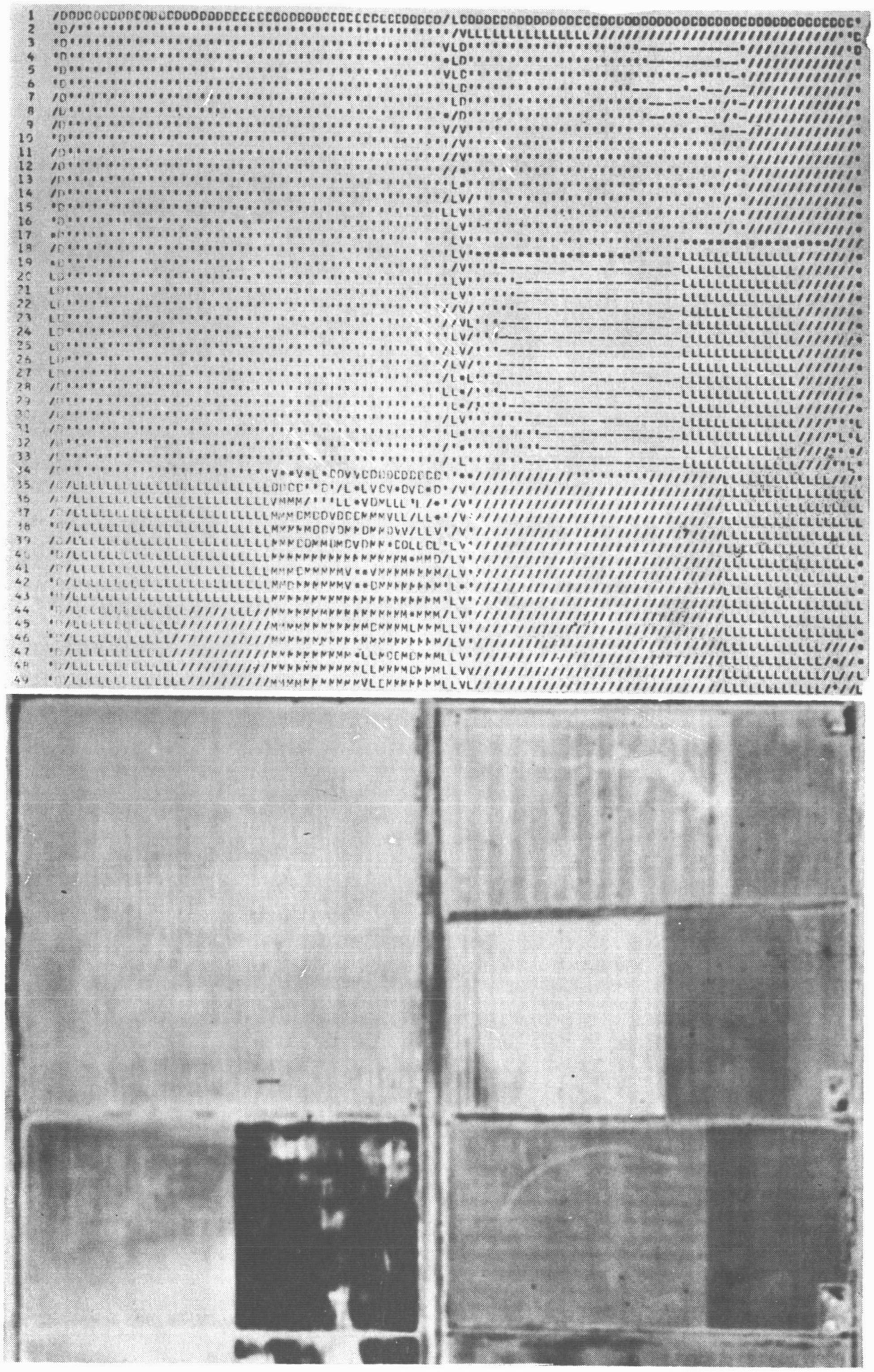


FIGURE 18 - A COMPARISON OF AERIAL PHOTOGRAPHS AND
A COMPUTER IMAGE PRINTOUT

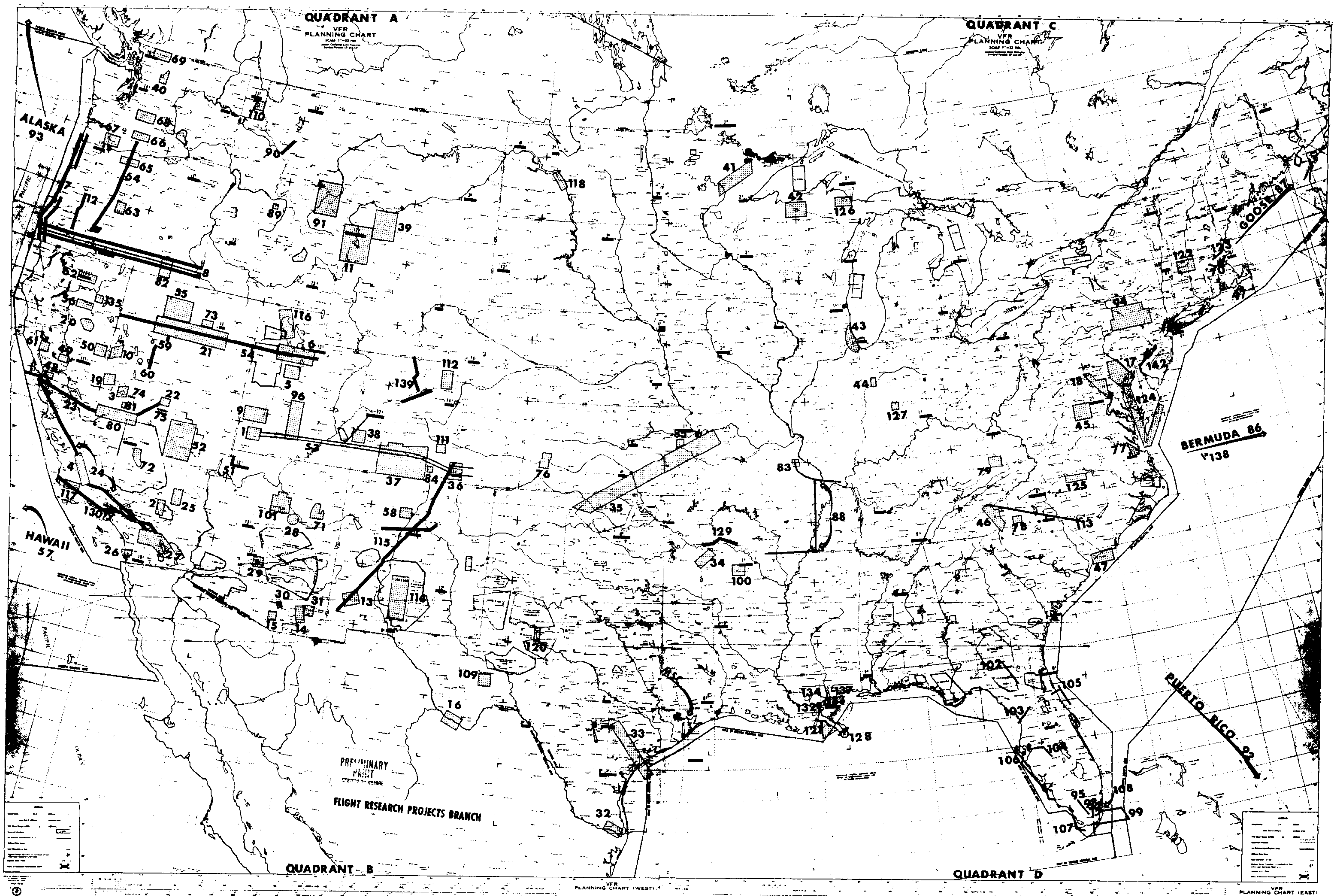



FIGURE 19 - NASA AIRCRAFT EARTH RESOURCES TEST SITES

<u>CONVAIR 240A AIRCRAFT</u>

AAS-5 ULTRAVIOLET IMAGER
RECONOFAX IV INFRARED IMAGER
MR62 AND 64 MICROWAVE RADIOMETER
ITEK MULTIBAND CAMERA
RC-8 METRIC CAMERA
T-11 AERIAL CAMERA

<u>LOCKHEED - P3A AIRCRAFT</u>

RS-7 INFRARED IMAGER
RC-8 METRIC CAMERA (2)
INFRARED SPECTROMETER

<u>PROPOSED FOR LOCKHEED - P3A</u>

13.35 GHz SCATTEROMETER
MODIFIED KA62 CAMERA CLUSTER
400 MHz SCATTEROMETER
INFRARED RADIOMETER
16.5 GHz SIDE LOOKING AIRBORNE RADAR
DUAL CHANNEL I.R. IMAGER
MULTIPLE FREQUENCY MICROWAVE RADIOMETER
LASER ALTIMETER

FIGURE 20 - EARTH RESOURCES OPERATIONAL SENSORS AS OF SEPTEMBER 12, 1967

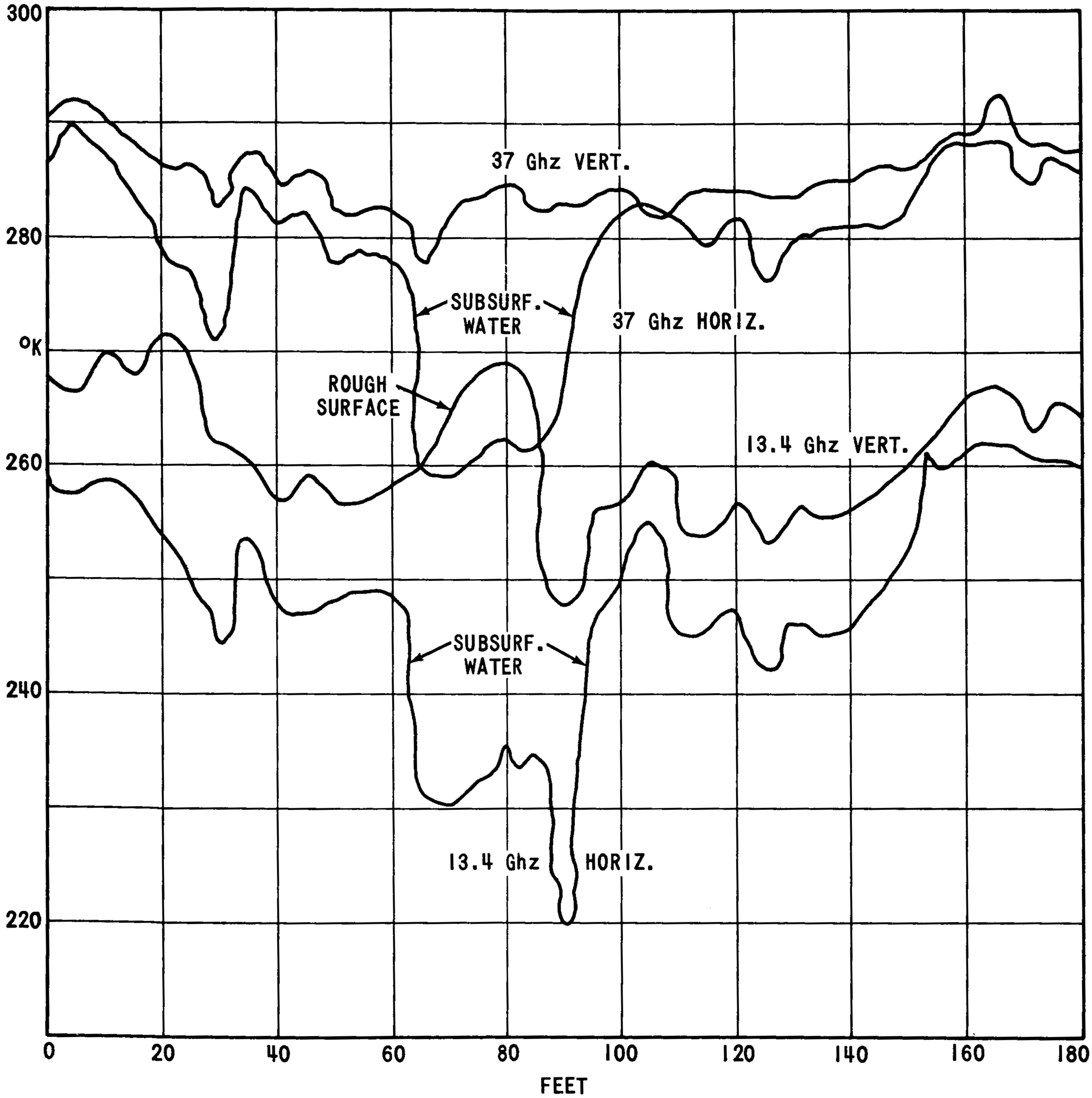
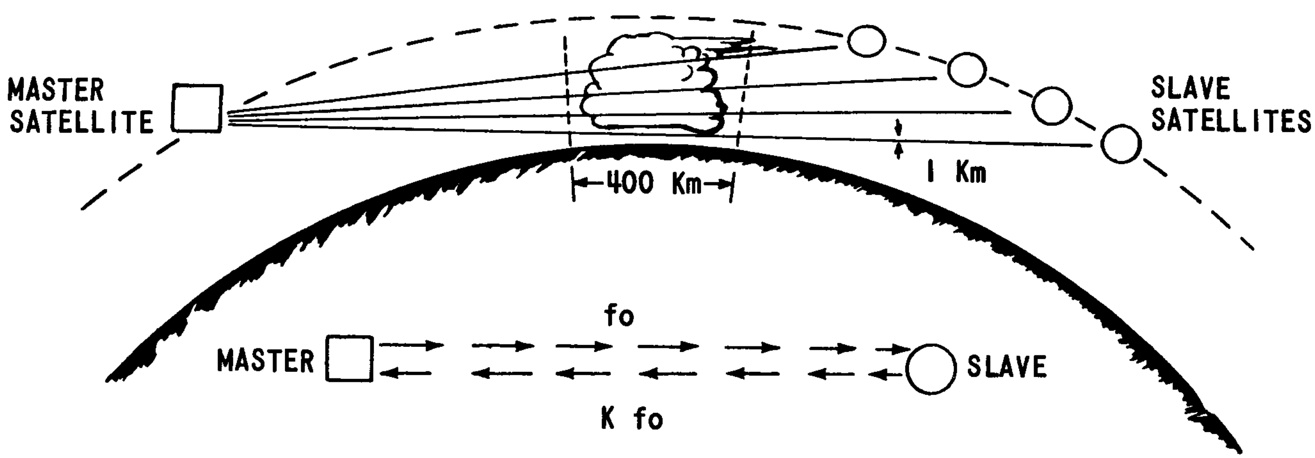



FIGURE 21 - MULTIFREQUENCY PASSIVE MICROWAVE SUBSURFACE WATER SURVEY, SPACE GENERAL CORP. WATER BODY SHOWS UP ONLY IN HORIZONTAL POLARIZATION. LOWER FREQUENCY SURVEY SHOWS BETTER PENETRATION OF UNDERGROUND MICROWAVE ENERGY




MEASURES PHASE CHANGE: $\phi(p) = \frac{1}{\lambda} \int_{-00}^{+00} (\mu - 1)\, dx$

$N(h) = \mu(h) - 1 \times 10^6$

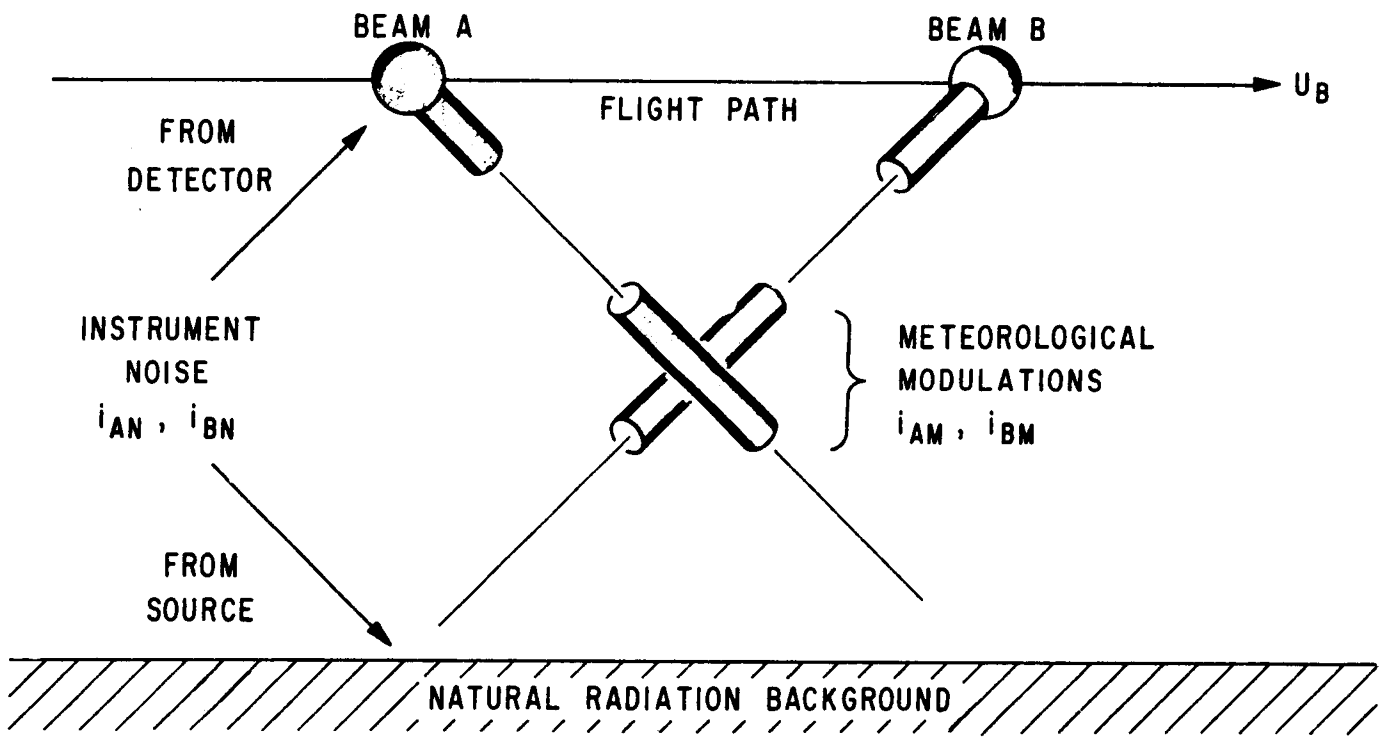
$N = 77{,}6 \frac{P_d}{T} + 72 \frac{e}{T} + 3{,}75 \times 10^5 \frac{e}{T^2}$

$\mu$ = REFRACTIVITY
h = HEIGHT
$P_d$ = PRESSURE OF DRY AIR
e = VAPOUR PRESSURE

FREQUENCY CHANGE, $\Delta f$, RESULTING FROM PASSAGE OF 2,000 MEGA-HERTZ SIGNAL THROUGH A STANDARD ATMOSPHERE AT DIFFERENT ALTITUDE, h.

| h (Km) | $\Delta f$ (HERTZ) | h (Km) | $\Delta f$ (HERTZ) |
|---|---|---|---|
| 0 | 2,300 | 10 | 707 |
| 2,5 | 1,770 | 20 | 206 |
| 5 | 1,292 | 40 | 16 |

FIGURE 22 - RADIO OCCULTATION TECHNIQUE




$$\underbrace{\langle i_A \; i_B \rangle}_{\text{TWO BEAM PRODUCT MEAN VALUE}} = \underbrace{\langle i_{AN} \; i_{BN} \rangle + \cdot \cdot \cdot}_{\text{NOISE TERMS DECREASE WITH } T^{-1/2}} + \underbrace{\langle i_{AM} \; i_{BM} \rangle}_{\text{LOCAL INFORMATION}}$$

**FIGURE 23 - CROSSED BEAM CORRELATION TECHNIQUE**

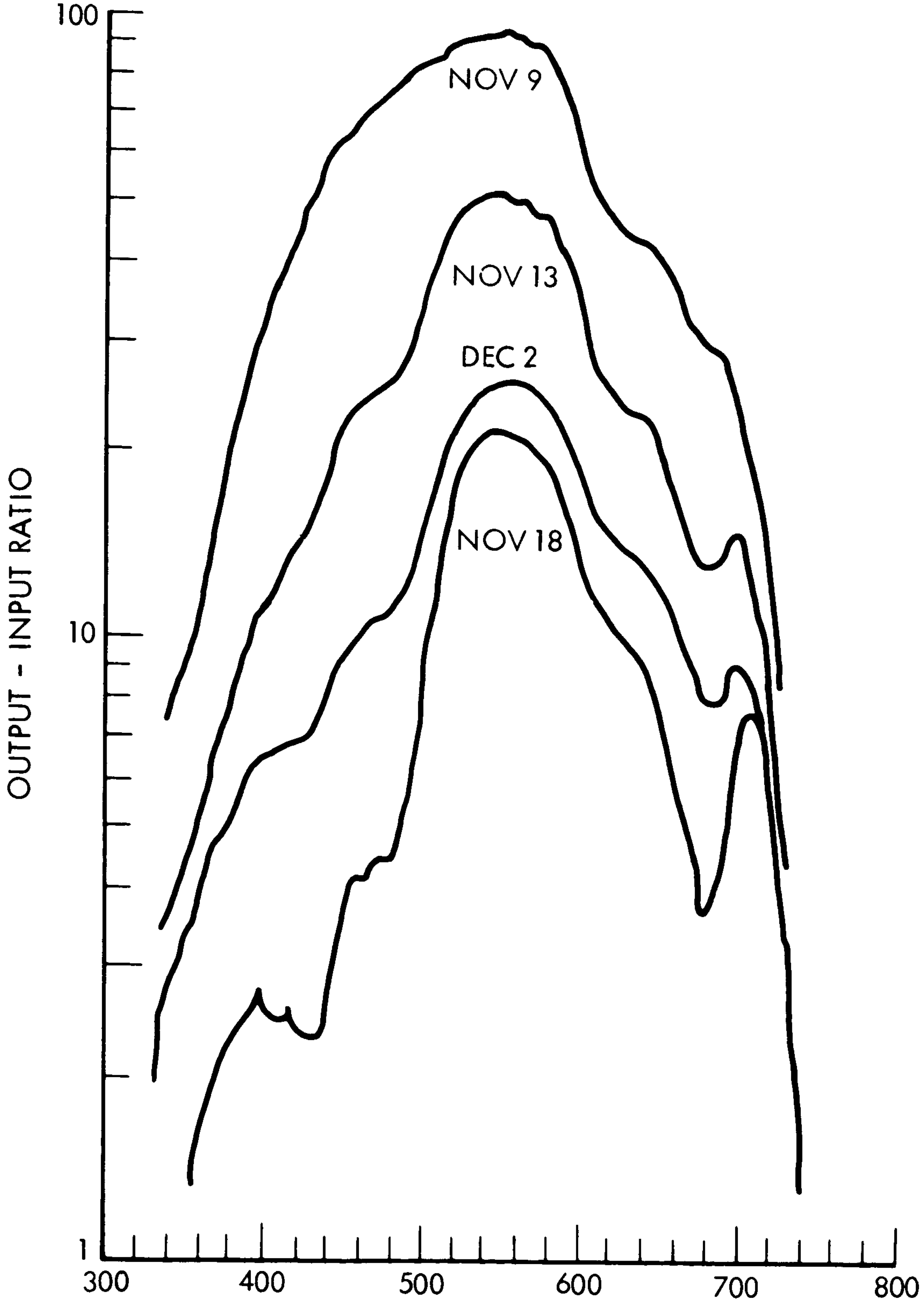



FIGURE 24 - SPECTRAL ABSORPTION OF LIGHT BY WATER WITH VARYING CHLOROPHYLL CONCENTRATION, TRW NASW-1658

BELLCOMM, INC.

Subject: Current Program and Considerations of the Future for Earth Resources Survey by Remote Sensing - Case 710

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B. E. Sabels

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